Chapter 18

Rodent Control and Island Conservation

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Introduction

On June 15th 1918, the SS Mokambo ran aground on Lord Howe Island in the south-west Pacific (Long, 2003). There was little loss of life, that came later. The ship was infested with Ship rats, *Rattus rattus*, and these went ashore with the human survivors while the ship was temporarily beached. In the years that followed, rat predation resulted in the extinction of the at least five species of the island's endemic birds, including Robust white eye (*Zosterops strenuus*) and Lord Howe Island Thrush (*Turdus poliocephalus vinitinctus*) and the serious decline of populations of many others. A variety of other taxa was also affected including molluscs, insects and amphibians. Another recent event was the devastation caused by the arrival of roof rats on Big South Cape Island, New Zealand, in the early 1960s, when several endemic birds species were quickly extirpated (Thomas and Taylor, 2002). We know of these extinctions because they occurred when accurate faunal records were available. However, such events have occurred in all of the world's oceans for thousands of years, resulting in the extinction of many species which we only know from the fossil record or not at all. The immense impact of alien rodents on the faunas of oceanic island continues to this day (Blackburn *et al*., 2007; Varnham, 2010).

Such impacts have been long recognised. In 1958, Charles Elton described the effects of alien invasives on island ecosystems as "one of the great convulsions of the world's fauna and flora" (Richardson and Pýsek, 2007). Modern ecologists are no less alarming in the words used to describe this phenomenon and impacts on biodiversity are described, for example, as "immense, insidious and usually irreversible" (Veitch and Clout, 2002). The spread of invasive rodents has been well documented (Atkinson, 1985; Long, 2003). The main species involved are the Norway rat (*Rattus norvegicus*), roof rat (*R. rattus*), the house mouse (*Mus musculus/domesticus*) and the Polynesian rat or Kiore (*Rattus exulans*). The first three species originated in Asia and had become widely distributed, via terrestrial routes, before spreading from Europe to the world's oceanic islands during the period of European ship-borne exploration and subsequent migration. The Polynesian rat was also native to the Indo-Malayan region and is thought to have been spread across the Pacific by the Polynesian peoples, and their ancestors, reaching the Hawaiian islands by 800 A.D. (Atkinson, 1985).

The most well-known impact on native faunas of rodent aliens is, of course, predation, because this is most readily observed and identifiable. Other less obvious impacts may be equally important, however, such as competition for food resources and nest sites. There are certainly even more subtle effects, for example the prevention of vegetal re-growth cause by seed depredation. This may result in broad impacts on a wide variety of taxa, through changes to the composition of native flora, but may go largely unnoticed in short-term studies. Courchamp *et al*. (2003) examined the extensive range of impacts, both obvious and insidious, of mammalian invasives on islands, including those of rodents. There is no room for doubt that any rodent species introduced as an alien to an oceanic island will have an important impact on the island's biodiversity. In many cases the effects will be catastrophic, as clearly recorded by Atkinson (1985) and Courchamp *et al*., (2003). These impacts are often accelerated because endemic faunas have developed no behavioural mechanisms to protect themselves from small ground predators, as seen in dramatic form in the consumption of live albatross chicks by house mice on Gough island (Cuthbert and Hilton, 2004).

Almost as soon as the adverse impacts of alien rodents on islands were recognised conservationists began projects to mitigate, or even reverse, their effects. Fortuitously, this enlightenment coincided with the invention and development of the anticoagulant rodenticides (Chapter 6). These compounds have been the mainstay of projects for both the long-term management and total removal of rodents from islands. One of the first such projects to use rodenticides was that carried out on Nonsuch Island in the Caribbean to protect the Bermuda Petrel (*Pterodroma cahow*) (Wingate, 1985). All subsequent projects have followed a similar pattern, although methods have differed in detail.

Essentially there are two principal strategies for the management of alien rodents. The first, eradication, is employed on relatively small islands where logistics permit this approach. The size of islands that are capable of eradication is steadily growing as new rodenticide application techniques are employed (Brooke *et al*., 2007). The advantage of this approach is obvious in that benefits are long-term, provided rodents do not return to the islands from which they have been removed. Where logistics, particularly the size of islands, prevents eradication a second approach, long-term rodent management, is adopted. This has the disadvantage that action is required on an ongoing basis but many such projects are now in place around the world (see for example Coulter *et al*., 1985; Zino *et al*., 2001).

In this chapter we describe the impacts of alien invasive rodents on natural ecosystems, with emphasis on oceanic islands, and review management techniques to mitigate their effects.

Island invasions by rodents

Most rodent species are highly adapted, *r*-selected, boom-or-bust strategists (Chapter 1). Such pre-adaptation to invasiveness allows them quickly to take advantage of abundant new resources and is why rodents are among the most successful mammalian colonisers of islands. Atkinson (1985) reported that 82% of the world's 123 major islands and island groups were inhabited by one or more of the common commensal rodent species. Colonisation continues at the rate of almost 6 islands every two decades (Russell *et al*., 2007a). Undoubtedly, rodents are able to colonise islands without human assistance. The swimming abilities of some species are well-known and, for example, Norway rats are capable of swimming distances of up to 1 km (Russell *et al*., 2007b). However, the ability of rodents to colonise oceanic islands that were distant from naturally-populated land masses came only with the assistance of human seaborne movement.

It is thought that the earliest substantial human-mediated movement of rodents began around 1500 B.C. with the colonisation of the islands of the western Pacific by the Lapita peoples, who transported Polynesian rats with them wherever they settled, by accident or intention (Atkinson, 1985). The translocation of *R. exulans* continued across the Pacific with the true Polynesian peoples and, by 1000 A.D. these rats and their human vectors had reached the islands of New Zealand, Easter and Hawaii. Polynesian rats are the smallest of the common colonising rat species and are thought to be less damaging thant Norway and Ship rats. Also, they have been a part of the ecosystems that they now inhabit for so long that some argue that ecological equilibrium has been reached. However, for example, recent studies on Henderson island in the Pitcairn group confirm the severe ongoing impacts of Polynesian rats on the island's population of Henderson petrel (*Pterodroma atrata*) and other seabirds (Brooke *et al*., 2004). An eradication programme is now planned. There is no doubt that impacts of Polynesian rats on the ecosystems of the island of the Pacific have been extremely severe and continue to this day.

The other three commensal rodent species which now colonise islands worldwide all spread from the Indo-Asian land mass. The first species involved was *Rattus rattus*. This was the main rat pest in Europe throughout the Middle Ages and was on board ships of the first European explorers of that time. Consequently, many of the islands of the Atlantic and Indian oceans were colonised in the 'Age of Discovery' during the period 1500 to 1700 A.D (Atkinson, 1985). European excursions into the Pacific were rare at that time and this probably explains why few islands were then inhabited by Ship rats. Norway rats appear to have reached Europe very soon after 1700 A.D. and, because this event is relatively recent, records of their spread are probably reasonably accurate (Long, 2003). Not only did Norway rats displace ship rats as the principle European rodent pests on land but, importantly for island colonisation, they replaced them on ships as well. Consequently, from 1700 onwards, there was a rapid expansion in the numbers of island around the world that were infested with Norway rats. House mice originated in central Asia but, probably because of their diminutive size, less is known about the chronology of their invasions of islands. What little is known is documented by Long (2003). Atkinson (1985) reviewed the distribution of the three species among the islands of the Atlantic, Pacific and Indian oceans and the current situation has not changed much since that time (Table 1). Long (2003) provides detailed information of the distribution of these alien invasives.

Although not strictly a rodent, mention should also be made of the European rabbit (*Oryctolagus cuniculus*). This species has been purposely transported to more than 800 islands worldwide (Long, 2003). Because of its herbivorous food habits it does not predate native fauna but its impacts on native floras are very profound, with consequent catastrophic effects on endemic faunas (Courchamp *et al*., 2003). The methods of dealing with rodents on islands, which will be explored in the remaining sections of this chapter, can with some appropriate modification be extended for use against rabbits. In some of the projects described below the removal or rabbits and rodents were concurrent using the same techniques (e.g. Oliveira *et al*., 2010).

Table 1. Distribution of commensal rats among major islands and island groups. From Atkinson (1985).

Rat species present	Number of islands or island groups			
	Pacific Ocean	**Indian Ocean**	**Atlantic Ocean**	**Total**
R. exulans alone	2	-	-	2
R. rattus alone	6	17	3	26
R. norvegicus alone	4	1	5	10
R. exulans + *R. rattus*	7	-	-	7
R. exulans + *R. norvegicus*	6	-	-	6
R. rattus + *R. norvegicus*	4	4	5	13
All three species	15	-	-	15
One or more unidentified commensal rat species present	9	7	6	22
Free of probably free of commensal rodents	12	5	5	22
TOTAL	65	34	24	123

Management strategies

The introduction of rodents as alien invasives to new regions is as a major challenge to modern wildlife conservation worldwide (Veitch and Clout, 2002). At first, the complete removal of rodents seemed impractical and early management efforts focused on control, rather than eradication. The first documented successful island rodent eradication dates back to 1951 when Norway rats were removed from Rouzic Island (3.3 ha), off the coast of France (Lorvelec and Pascal, 2005). This and other early successful eradications were generally unintentional by-products of normal rodent control efforts, however, serious consideration was subsequently given to removing rodents from islands intentionally. In the 1980s more refined techniques for eradicating rodents from larger islands were developed, with a 'landmark' event occurring in 1988 when Norway rats were eradicated from New Zealand's Breaksea Island (170 ha) (Taylor and Thomas, 1993). Eradication of introduced rodents from island ecosystems has now been achieved on over 400 islands worldwide (Database of Island Invasive Species Eradications, 2013). Among documented eradication attempts, 90% have been successful, but this estimate may be inflated as success is more likely to be reported than failure. Most of these island eradications took place in Australasia, particularly in the islands surrounding New Zealand (Howald *et al.* 2007) and much of what we now know about the control of alien invasive rodents is derived from work done by New Zealand scientists.

The Breaksea project, and other early programmes, relied on the deployment of rodenticide baits by hand in durable bait stations, usually set out in grid patterns. However, examination of the New Zealand records indicates that eradication success on larger islands coincides with the development of aerial (i.e. helicopter) bait delivery first employed in the late 1980s (Clout and Russell, 2006). Since that time there has been a rapid growth in the size of islands on which rodent eradication has been achieved. To date, the largest island where rodents have been eradicated is Campbell Island (11,300 ha) (McClelland and Tyree, 2002). This campaign, conducted in 2001 (see below), utilised aerially-broadcast brodifacoum bait to remove Norway rats (Table 18.2). A programme now in progress on South Georgia, if successful, will be larger still. Other projects to remove rodents from large islands using aerial bait applications have also taken place in North America, including Anacapa (296 ha) (Howald, *et al*., 2009), and Rat Island (2800 ha) (Salmon *et al*., 2008) and Langara Island (3270 ha) (Kaiser *et al*., 1997).

Table 18.2. Successful island eradications of rodents from New Zealand islands up to 2007. Letters are G for ground-applied baits, T for Trapping and A for aerially-applied baits. From Broome *et al*., 2010.

Year	**1960-69**	**1970-79**	**1980-89**	**1990-99**	**>2000**	**TOTAL**
M. musculus			1	11	3	15
R. exulans		1	3	23	6	33
R. norvegicus	2		9	19	12	42
R. rattus			2	8	7	17
TOTAL	2	1	17	59	28	107
Largest size (ha)	1	1	170	1,965	11,300	
Technique	G	G,T	G,A	G,T,A	G,A	

The roof rat has been eradicated from the most islands worldwide (*n*=159), followed by Norway rat (*n*=104), Polynesian rat (*n*=55) and house mouse (*n*=30). Rats have now been removed from 14 islands with areas of more than 500 ha. However, neither roof rats nor house mice have been eradicated from an island larger than 1,000 ha. House mice eradications also have the highest failure rates at 19% of operations, with other reported failure rates for mice as high as 38% (McKay *et al.* 2007), followed by Polynesian rat (10% failure), roof rat (8%) and Norway rat (5%) (Howald *et al.* 2007).

The removal of rodents from many offshore islands has enabled significant conservation gains but there are many situations where eradication is still not, and may never be, feasible. Where eradication is not possible, mitigation of the threat caused by rodents must be achieved by sustained control action and this requires good knowledge of both pest and prey ecology (Innes 2005a, b). On the New Zealand mainland, 'best practice' techniques for ongoing rodent control have been developed by the Department of Conservation (DOC). These predominately rely on the conservative method of bait application by hand using bait stations, as the risks of primary and secondary poisoning using aerially-dispersed anticoagulants on mainland sites are too high (Eason *et al*,. 2002). In most situations intervention is timed to protect vulnerable species either during the breeding season or during rodent population explosions and is not applied year round. A similar strategy is adopted in the long-running programmes to protect *P. madeira* on the island of Madeira (Zino *et al*., 2001) and *P. phaeopygia* in the Galapagos (Cruz and Cruz, 1996). Bait station design has advanced considerably to prevent non-target access and bait is made 'captive' to prevent removal and caching. In New Zealand, rodent abundance is monitored using a standardised tracking index to assess the success of control programmes (Gillies and Williams, 2004).

Sustained control of rodents on the New Zealand mainland generally integrates non-anticoagulants (i.e. 1080) with first-generation and second-generation anticoagulant compounds (Eason *et al.* 2010a). Current best practice dictates that bait types, toxins and lures need to be regularly changed to prevent environmental contamination (Eason *et al.* 2002) and the development of bait shyness (Clapperton, 2006). There is increased scrutiny of the continued use of the more potent second-generation compounds, such as brodifacoum, which are only used in certain situations (Eason *et al.* 2010a). There are also best practise guidelines for kill trapping but this is not used without concurrent use of poisons because traps require frequent servicing and may not achieve operational targets when rat numbers are high (King and Moller 1997). Also, rodent species are not equally trappable and there are further differences both among individuals and between sexes of the same species (Clapperton, 2006).

Whilst management strategies adopted on mainland New Zealand for removal of alien invasive rodents currently focus on poisons and traps, both pose risks to non-target species. Rodenticides in particular may harm the environment (see below), as they are both non-specific and obviously toxic (Chapters 6, 15 and 16). An alternative approach is ecologically based rodent management. This combines multiple techniques, such as the reduction in refuge habitats (i.e. habitat manipulation), trap barriers, biological control and the use of rodenticides at key times. Best results are generally achieved when a combination of techniques is applied (Singleton, 1997) and the choice of techniques depend on ecological issues, agronomy, environmental awareness and socio-cultural considerations. Researchers have clearly demonstrated the relationship between rodent activity and the availability of food sources in urban areas (Figgs, 2011) and highlight that simple sanitation and rodent-proofing measures could be a very cheap means of reducing rat infestation rates (Promkerd *et al*., 2008). Within agricultural systems, researchers have demonstrated that the ecological based management can increase food production in comparison to farms where conventional management techniques are used (Jacob *et al*., 2010) and can be more cost-effective than conventional control measures (Brown *et al*., 2006). However, it remains in question whether these principles can find widespread utility in conservation where logistical problems and the requirements for immediate effects are paramount.

Management Tools

Eradications

Removal of introduced rats and mice from ecosystems in which they are harming biodiversity is one of the most powerful conservation tools available to permit recovery of endangered species. Although the objective of some projects is the long-term protection of area where complete removal of rodents is impossible, the majority are focused upon eradication. Rodents have been successfully removed from islands from the high temperate latitudes, to the equatorial islands and atolls of the inter-tropical convergence zone (ITCZ). These programmes have generally applied the same standardized approaches and methods primarily developed by conservation practitioners from New Zealand. Regardless of the size, location, or even species targeted for removal, each project has followed similar principles. These continue to be applied successfully to this day, involving applications of palatable baits containing rodenticide delivered into every potential rodent territory, so that all rodents have access to the bait. Timing of bait delivery is ideally when the target species is not breeding, is most likely to consume the bait and risks to native species from either the rodenticide or disturbance from the operations themselves is minimized or can be mitigated appropriately.

Many eradication programmes occur on islands that are managed by governmental conservation agencies, such as National Parks and Wildlife Refuges, which seek to protect endangered, and sometimes endemic, species and to restore island biodiversity. The use of rodenticides in these sensitive ecosystems presents a dilemma for ecologists because of the negative perception of pesticides held by some members of society. Proposed rodenticide use, regardless of the island, culture or socioeconomics of inhabitants, will invariably raise concerns about the safety for non-targets, including humans where present, and the need for risk mitigation. Thus, the precautionary principle is often applied, and programmes are not conducted, unless risks are known and either effectively mitigated or accepted. For long-term sustainability of these programs and projects, and to ensure the availability of the necessary tools in the future, all programmes must be compliant with appropriate regulatory requirements. They must also have the support of communities, at the local, regional and even national levels, which recognize the project's conservation goals. The application of rodenticides during eradications is a one-time event and without subsequent release of rodenticides into the environment. Once eradication is achieved, ecosystems go through significant beneficial changes, endangered species recover and biodiversity is protected for the future.

Rodenticides

In virtually all rodent eradications, a rodenticide in a bait matrix is the primary removal tool, and this remains the only proven method in use today for large and more complex islands. Such campaigns require rodents to seek out and consume a lethal dose of rodenticide bait. However, rodent populations are well known for the inherent variability of their foraging behaviour (Chapter 1) and physiology, especially tolerance/resistance to anticoagulants). This increases the likelihood of survivors when a selection pressure is universally applied to a rodent population, such as in a poisoning campaign. Thus the bait, and the rodenticide used in it, must accommodate this inherent variability, which might otherwise result in eradication failure and jeopardize future attempts to remove rodents. From the perspective of an eradication programme, the ideal bait would be:

- palatable and nutritious enough to overcome competition with naturally-occurring food sources,
- toxic to rodents at a single feeding,
- safe to non-target species,
- likely to remain in the treated environment in good condition for long enough to allow rodents to take a lethal dose but not to become a long-term risk to non-targets,
- readily manufactured into a pellet or block form for hand delivery into bait stations and/or broadcast (aerial or hand), and
- should not cause bait shyness or aversion.

Of course, no such ideal exists and trade-offs are made in the design of programmes to overcome any limitations. Bait used in an eradication programme must always be palatable and not elicit any bait shyness but a compromise between how toxic the bait is to rodents and risks to non-target species is often made.

The most commonly used rodenticides for eradications are the anticoagulants and both the first- and second-generation compounds (Chapter 6) have been successfully used worldwide. Their advantage is a delayed onset of poisoning symptoms, which minimizes the risk of bait shyness commonly seen with the acute rodenticides. Rodents are not believed to associate the symptoms of poisoning with the toxic bait and continue to feed on bait until a lethal dose is consumed.

Rodents usually must feed on first-generation anticoagulant baits for several days to illicit a toxic effect. First-generation anticoagulants are used successfully in island eradications most frequently when bait stations are used, rather than in broadcast baiting, perhaps because of the sustained availability of bait over a long period of time in bait stations. The major advantage of the first-generation anticoagulants over the second-generation is a lower, but not negligible, risk to non-target species though secondary poisoning.

Notwithstanding this, the second-generation anticoagulant brodifacoum, at a concentration of 20-50 ppm, is the most common rodenticide used in eradications worldwide (Howald *et al*., 2007). Strictly from an efficacy perspective, the second-generation anticoagulants offer the highest probability of successful removal of rodents because they:

- are highly toxic to a wide range of rodent species, including all the main alien invasives and are often lethal at a single feeding,
- are relatively resistant to metabolism therefore, cumulative small exposures via primary (or secondary) routes will lead to a toxic effect,
- have delayed onset of symptoms after ingestion of a toxic dose - typically 24-72 hours for symptoms to develop and mortality within 3-10 days,
- can overcome any inherited resistance or tolerance observed with other rodenticides (which may be of importance on islands with historical use of rodent control).

However, the second-generation anticoagulants are also toxic to non-target species, particularly to mammals and birds. Thus a requirement for maximizing efficacy and ensuring safety is an understanding of the risks of their use and an ability to mitigate them (see below).

Bait Matrix

Rodenticide baits are designed for high palatability, good nutritional content, are shaped into forms that are compatible with to the method of application and formulated to accommodate the climate in which they are to be used. For broadcast applications the baits used are mainly compressed cereal-based pellets, each of 1-10 g, designed to be released through a hopper and of sufficient mass to penetrate forest canopies. Bait station operations typically use bait blocks, usually about 20 g each, impregnated with wax to bind the block together, and offering protection from wet and humid conditions. Both baits typically satisfy most of the target population's nutritional demands, and must be palatable to all rodents to compete with native food resources on the island. However, natural food supplies are limited in many island ecosystems and rodents have evolved efficient foraging strategies to find these scarce resources. Therefore, when rodenticide baits are deployed in these situations, often at rates of many kilograms per hectare, rodents readily find and consume them.

Bait Delivery

As stated previously, a fundamental requirement of rodent eradication is to deliver bait into the territories of all rodents present. Also, sufficient bait must be available for all rodents to have access to bait for long enough to overcome any social, physiological, and behavioural barriers to consuming a lethal dose. Bait delivery is typically achieved by one, or a combination of methods. These are bait stations spaced at regular intervals (often in a grid pattern) and filled and re-filled by hand, broadcast baiting either by hand or with a bait spreader suspended beneath a helicopter, or by other mechanical means. The use of helicopters to spread bait has facilitated the successful conservation efforts on much larger and more topographically complex islands, particular those with steep cliff sides, inaccessible on foot and rendering bait stations unfeasible.

Bait Stations

Bait station eradications involve the use of stations, either commercially-available stations or locally-made, laid out on a grid pattern. Of course, at least one station should be present in every rodent territory, although rodents will increase the size of their territory if neighboring animals are removed during baiting.

Stations are visited, checked and bait replenished on a regular basis to ensure that bait is available consistently and in adequate quantities to kill the local rodents at a rate faster than they can replace themselves through breeding (Parkes, 1993).

The density of the grid layout (i.e. distance in each direction between stations) varies depending on the ranging movements of the target species and the environment in which they live. Typically, in temperate climates, spacing of 100m x 100 m (i.e. one station per ha) ensures enough stations to intercept all Norway rats. However, research has shown that roof rats may be best treated using 50 m x 50m spacing (4/ha) to achieve eradication over the same time period (see Thomas and Taylor, 2002). Removing house mice with bait stations may be very difficult because of their limited ranging movements, and may require stations spaced at 5-10 m intervals (Thomas and Tayor, 2002; Oliveira *et al*., 2010). Even working with these optimal grid densities, there are examples of failed projects (e.g. Howald *et al*. 2004), where bait station density may have been inadequate to intercept all rodents. Also, there may be a trade-off between bait point density and speed of control.

The use of bait stations in rodent eradications has several advantages. Bait placement is controlled, and for the most part only the target species, and non-targets of the same or smaller size, have access to it. This serves to reduce primary exposure. Block baits may be held in bait stations on wires or rods because loose particles may be removed by rodents and left in the open. Bait not consumed is easily recovered when bait boxes are used. Also, managers can monitor the progress of the eradication through observing bait uptake and its decline over time (see Monitoring below). The goal is to reach a point where there is consistently no bait uptake by rodents from bait boxes and this indicates successful eradication.

Bait station eradications also have disadvantages. Relative to broadcast baiting, the time to eradication may be longer due to the behaviour of the target species. This is because of the time taken to overcome neophobic responses, both to bait stations and bait (Gill and Wein, 2012), and because some individuals may dominate stations leading to bait not being available to subordinate rodents until dominants have been killed (Thomas and Taylor, 2002). The requirement to reach all bait stations on several occasions in difficult terrain may result in high labour costs and increased safety risks to staff. Sometimes mixed schemes are required in which bait stations are used where topography allows, with broadcast baiting elsewhere (Oliveira *et al*. 2010). On some tropical islands, the presence of land and hermit crabs may prevent the use of ground-secured stations because of the attractiveness of the bait to these crustaceans. Crabs may congregate at bait stations and consume bait, excluding some rodents. Bait stations may be lifted off the ground on platforms to exclude crabs but this incurs a risk also of excluding some rodents, and thus the success of the programme. Lastly, the longer the stations are left in place the greater the risk to non-target species, via both primary and even secondary exposure (see Howald *et al*., 1999).

Bait Station Strategies

There are two strategies for rodent eradications with bait stations (Thomas and Taylor, 2002). Both involve setting out stations in a grid pattern, however, the amount of land area treated at one time will vary depending on logistical considerations.

The 'rolling front' technique involves setting out bait stations on only a portion of the area to be treated. These are checked and replenishing with bait until takes decline to zero, or close to zero, indicating the removal of rodents from the treated segment. Workers then move on to bait the neighboring segment. The stations initially baited may be left with bait to kill any survivors and to intercept any rats that may come back into the area already treated. This cycle is repeated, segment by segment, until the entire island has been treated. The advantage of the rolling front technique is that relatively few field staff are needed at any one time. However, the disadvantage is that the time to eradication rodents from the island is prolonged. Additionally, spatial or temporal gaps may be present where segments meet, leading to some areas being unbaited and putting eradication at risk.

The 'one-off' approach arms all of the bait stations simultaneously across an island. All bait stations are checked at the same schedule, ensuring that all rodents have access to bait, both spatially and temporally. The eradication progresses synchronously across the island leading to a more efficient use of resources compared to rolling front. However, regardless of method used the number of person-days needed to service stations is similar. Of course, the number of person-days needed increases with the size of the island and the number of stations used, and increasing complexity with the management and servicing of a larger staff. The one-off approach seems to offer the most efficient use of resources, the probability of eradication in the shortest time possible and is likely to be the most reliable.

Broadcast baiting

The application of techniques from agriculture and forestry for seeding, fertilizing, and pesticide application has revolutionized rodent eradications by facilitating applications on larger and more rugged islands. Bait containing a rodenticide in small 1-2 g pellets is spread evenly across the entire infested land mass, either by gloved hand or by mechanical means, often a specialized bucket-spreader suspended beneath a helicopter. If carried out efficiently, all rats have simultaneous access to the bait, thereby overcoming many of the disadvantages of the use of bait stations. However, broadcast baiting has an important disadvantage; it involves greater risk of exposure of non-target species. This requires careful environmental risk assessments and implementation of risk mitigation strategies (US Fish and Wildlife Service, 2007). Broadcast baiting is also usually inappropriate for inhabited islands.

Conservation practitioners are now commonly using aerial broadcast techniques on large islands, and those with inaccessible cliffs, delivering bait into areas that are impossible to reach on foot. Broadcast application ensures bait is available to all rodents at the same time, with little intraspecific interaction because the bait is widely distributed as a food resource and indefensible by individual rodents. Thus, eradication programmes using broadcast baiting may proceed more quickly than when bait stations are used. For rodents that are actively foraging, the majority are found dead within 5-7 days (Howald *et al*., 2009).

Bait is sown (an analogy with broadcast seeding) at a fixed application rate, usually expressed as $kg.ha^{-1}$. The bait may be either uniformly distributed across the entire land mass to be treated or application rates may be stratified by habitat type. Application rates are not usually set to accommodate specific rodent population densities because these are rarely known. Instead the objective is to ensure bait is uniformly available for at least three or four days to allow enough time for rodents to overcome any behavioral constraints to consuming a lethal dose. Applications rates are adjusted to accommodate potential loss of bait to other animals present, such as native rodents, birds and (occasionally) molluscs and crustacea. The rate of degradation of bait by climatic conditions, such as rainfall must also be considered.

Rigorous planning is essential in broadcast applications to ensure accurate deposition of bait. Straight line transects or baiting lines are usually established, with the distance between transects dependent on the breadth of the swath along each transect. However, transect disposition is entirely dependent on local topography. After bait application is complete along transects, typically from coast to coast on large islands, the next transect is treated. Applications are conducted sequentially until the entire area to be treated is covered.

Hand-broadcasting involves a single applicator, or a line of applicators, spaced at regular intervals, usually 10-25 m, walking along a pre-defined compass bearing, or guided by GPS (global positioning system), and stopping at regular intervals (5-25 m) to spread bait. The entire line of baiters works as a single unit, keeping the line together and moving forward systematically. Alternatively, where GPS precision is high, pre-loaded points can guide baiters to specific locations, and allows for monitoring of where bait has been applied. The precision of application rates by hand baiting is high because the baiters are walking the island applying bait evenly across the surface area of the island. However, hand application can be very labour-intensive and safety risks to personnel need to be carefully considered in difficult terrain.

Helicopters greatly increase the speed of application and size of islands which can be treated. Using these aircraft makes eradication feasible on islands where hand-baiting is impossible due to size or difficulty of terrain. The helicopter can fly a reliable straight line unaffected by topography and limited only by the amount of bait it can carry in the bucket, the need for reloading and refueling and weather. Transect or swath width, which may be between 5 and 100 m, is determined by how far the bait is spread from the bucket. The application is monitored by an onboard computer, connected to a GPS and light-bar informs the pilot, in real time, of the position of the helicopter relative to the intended transect and what adjustments in direction are required. The pilot retains control of bait application with a trigger control that opens and closes an hydraulic gate on the bucket.

Although aerial application is more efficient and quicker, several variables influence net application rates. These are helicopter ground speed, flow rate of bait through the bucket, weather (including humidity and cross winds), swath width, any planned overlap in swath width and surface area of the island. The higher the ground speed, the lower the net application on the ground and vice versa. The bait flows through the bait bucket by gravity, and the rate can be increased or decreased by adjustment of the orifice through which the bait discharges and the speed of the spinning paddle in the bucket, and at times must be adjusted depending on temperature and humidity due to bait clogging.

Of course, some variables are not under the control of operatives, such as weather and unpredictable events that force the pilot off the track (e.g. avoidance of birds, wind gusts). Eradication plans account for some of these variables with overlapping swaths. Typically, up to 50% overlap is planned to ensure that there are no bait gaps on the ground. For example, if a target application rate of 10 kg/ha is desired, the flow rate out of the bucket and a fixed flight speed may be set to apply 5 kg/ha in a given swath. With a 50% overlap in adjacent flight swaths, the total net application rate on the ground is 10kg/ha, the target application rate. Calibration of the equipment during test applications, and the influence of these factors on the bait density on the ground are always measured prior to the eradication operation. Active monitoring of the application using GPS data and ground-truthing confirms that the ground application rate is within expected parameters and if adjustments are needed made either to the helicopter flight speed or the bait bucket flow rate. Finally, the topography of the island has considerable influence on the net application rate on the ground. When bait is applied by helicopter, the steeper the slope the less bait is applied per unit area. For example, a slope of 37 degrees results in a 20% reduction in baiting density (viz. Pythagoras theorem).

Timing of Broadcast Applications

Unlike bait station eradications, where bait may be available to target rodents for many months and even years, and most non-target species can be protected from gaining access to the bait; broadcast eradications are substantially different. Bait is available to the target species for a limited period, typically measured in days or at most a few weeks, but during that time poses a significant risk of exposure and primary poisoning to non-target species. Thus, the optimum strategy for broadcast eradications is to time the eradications when the rodents are most likely to eat the bait, and ideally when the least number of individuals of non-target species are present in the treated area. In the temperate latitudes and dry tropics, best timing is at the annual food-dependent rodent population decline, when rodents are not breeding and any migratory species present have completed breeding and moved away from the island.

In the tropics, there may be no obvious annual food-dependent population cycle, leaving no optimum window for successful rodent removing. Thus, eradication is best timed for the least impact to non-target species. For example, on Palmyra Atoll, a broadcast application was planned for when migratory Bristle-thighed curlews (*Numenius tahitiensis*), which overwinter on the atoll, were away on their breeding grounds in Alaska. The timing of the eradication for the boreal summer minimized the risk to shorebirds. When the majority of breeding birds returned to the Atoll for the winter, there was no bait available to put the birds at risk from primary exposure.

In most, if not all, cases in broadcast baiting, a second bait application is made 10-14 days after the first, to ensure that bait is available to those rats that have failed to take bait at the first application. This follow-up application also accounts for any rats that may have been in the nest, and unavailable to take bait, during the first. This phenomenon was observed recently on Palmyra Atoll, where a young rat was discovered alive weeks after the first broadcast, thus reinforcing the need to space the second broadcast as long as possible after the first. Typically, 10-14 days is sufficient delay between broadcasts but up to three weeks may be preferable. Unfortunately, a long delay between bait applications can be a significant logistical problem in remote locations because helicopters, equipment and personnel must stay on island for the next application.

Monitoring

Rodent eradications are usually carried out in stages each of which is dependent on the one before. In order to make rational decisions as the programme progresses it is necessary to monitor certain operations. Typically, monitoring is done to:

- ensure that implementation of the eradication programme is progressing as planned, that adequate bait is delivered where it is needed, bait is consumed and target rodents are being removed, mitigation strategies are working, risks/impacts from either the rodenticide or disturbance are within predicted range, predicted benefits to biodiversity are delivered (these are monitored in separate operations);
- comply with permits which may impose conditions on the use of rodenticides, other equipment and on habitat disturbance;
- contribute learning towards the development future projects, which is particularly relevant when working in new environments and in conditions in which there have been few successful projects.

Bait Application Monitoring

Monitoring bait application, both spatially and temporally is critical to meeting the first requirement of successful rodent eradication, that of delivering bait to every rodent territory. This facilitates the identification of areas where there might be inadequate bait coverage, which may result in rodents surviving the application. The use of GPS and global information system (GIS) software has become the standard by which bait application is monitored regardless of how bait is delivered - bait stations, hand or aerial broadcast or a combination. The use of this technology is fundamental to successful implementation of larger and more complex projects. GIS data, in combination with ground-truthing, verifies where bait was applied and at what rate, allowing managers to make decisions about additional applications. More importantly, it tells managers what potential rat territories did not receive bait. Because data are geographically linked, they can be uploaded to a GPS unit and/or onboard helicopter computer/GPS to direct additional applications. GIS is an extremely valuable tool for supporting decisions on the progress of eradication projects but the quality of data entered must be accurate, confirmed by ground-truthing and with proper initial calibration, to ensure that output is a valid representation of what is happening on the ground.

Bait station eradications greatly benefit from GIS monitoring, and this is most apparent in programmes involving large islands with many bait stations (e.g. Bell *et al*., 2007). Each station is geo-referenced and its data are uploaded into GIS systems to permit analysis at different levels of resolution, from single stations to blocks of stations and other subsets. At a minimum, the data collected are: the amount of bait put out initially and the amount consumed and added at each subsequent check. These data may be entered into small hand-held GPS-linked field computers. Data is downloaded from each unit and accumulated over time for each station. The quantities of bait removed by rodents from the stations may be used as an indicator of rodent activity over the duration of the programme. When this is reduced to zero and sustained for a pre-determined period, from several months up to 2 years, eradication can be declared to have been successful.

For aerial broadcast eradications, the GPS and onboard computer are linked electronically to the helicopter and bait bucket. The GIS software, linked to the GPS, is pre-loaded with flight paths and overlaid on an image of the island. The computer links these flight lines to the GPS, which guides the pilot along a pre-planned route and, in combination with visual cues, prompts the pilot to begin spreading bait. The onboard computer records the position of the helicopter at the point the bucket is opened by the pilot and bait flow begins. It then "paints" where bait is spread, both along the flight line itself and provides and records a visual estimate of swath width. The computer also records where the bait bucket is closed and therefore where no bait has been applied. Also, where there are sensitive habitats, such as water bodies or other areas, where no bait is to be applied, GIS data verifies the precision of the application.

Efficacy Monitoring

It is to state the obvious that rodent eradications require the complete removal of a target species from a defined location, such as an island. Missing any individual, which at worst may be a pregnant female, may result in the failure of the programme. This of course negates all financial investment, makes futile any non-target species impacts and any short term conservation gains obtained from the temporarily reduced rodent population. Thus, it is critically important to demonstrate that the project is successful in removing rodents and, if they are detected, to be able to respond to and implement an appropriate response to eliminate any residual individual in the treated area.

There are many different methods of measuring the effectiveness of an eradication programme and these involve both direct and indirect monitoring tools. Live traps, kill traps and camera traps are commonly used to detect rodents. If rodents are large and the terrain permits, direct observation maybe used, sometimes with the aid of white light or infra-red spotlights and other night-vision equipment. Some projects have utilized the capture and release of radio-collared individuals. Indirect indicators such as tracking plates, on which rodents leave footprints indicating their presence, and flavoured chew blocks, tags, sticks and cards, on which rodents leave incisor marks, are also effective. The most appropriate method depends on the nature of the island, climatic conditions and various logistical constraints, such as the frequency of access to treated areas. For example, wax census blocks may be highly effective in a cool, wet temperate environment, but ineffective in the desert or tropical islands where they melt in the sun or are attractive to land crabs. Regardless of the methods used, the principles of rodent detection remain the same - several different indicators, both direct and indirect, should be used across the entire treated area, or in carefully selected representative portions of it, to maximize the probability of detecting the presence and absence of rodents. Such indicators, when conducted prior to baiting, provide an initial estimate of population density for comparison with the situation during baiting and after the programme is completed. Data obtained prior to baiting may be used to identify critical areas for special consideration, such as preferred habitats of rodents. These areas are used to target post-treatment monitoring to areas where survivors are most likely. Of course, direct methods provide the most reliable evidence of the presence and absence of rodents but these are often the most difficult to conduct.

Rodents, because of their small size, cryptic colouration and nocturnal behaviour, are often very challenging to detect, particularly in very low densities. Therefore, final confirmation of successful eradication is usually done only after enough time has elapsed for the production of several rodent generations. This permits residual individuals to build up in sufficient number to be readily detected. In temperate ecosystems, the accepted standard is to wait two years, or at least two full breeding seasons. If no rodents are detected after two years, the eradication has very likely succeeded. In the tropics, where breeding is not seasonal, monitoring for rodents at one year may be sufficient time for residual rodents to reproduce in sufficient number to be readily detectable.

Monitoring data informs managers on how the bait has been applied, and the progress of the eradication, ensuring that decisions are made based on accurate situation assessments. Should a project fail to eradicate rodents, monitoring data is essential to provide insight into what may have caused failure, and to inform planning for future projects.

Monitoring benefits

All projects aimed at the removal of rodents for conservation have specified objectives but, once the immediate purpose of rodent eradication is achieved, the delivery of biodiversity benefits is often assumed rather than scientifically measured. However, it is important that initial project plans should include an element in which delivery of long-term conservation goals are directly measured. This information is an important justification for the project and provides valuable support for future funding applications. It may be sufficient to observe over time the recovery of a single, selected sentinel species, although broader biodiversity monitoring is obviously to be preferred. This is because the removal of rodents often has benefits which extend far beyond an increase in numbers of a single species, or group of species, that has been predated.

A thorough programme of benefits monitoring was conducted after the eradication of rabbits and house mice from Great Salvage Island (Oliveira *et al*., 2010). Protection from disturbance, nest site competition and predation of populations of small, burrow-nesting pelagic seabirds were the main purposes of the programme but wider biodiversity gains were also anticipated. After the successful eradications in 2002 to 2003, periodic botanical surveys revealed a dramatic recovery in the flora of the island which, in turn, supported increased populations of many invertebrate taxa. These provided enhanced food supply for several important species of reptiles and birds, the populations of which all showed major increases. Unfortunately, breeding success of the small pelagic seabirds could not be directly measured because their nests are inaccessible without unacceptable risk of disturbance and nest burrow collapse. However, long-term monitoring was undertaken of a larger species, Cory's shearwater (*Calonectris diomedea*), whose nests could be visited. This showed an immediate improvement in breeding success after the eradication programme (Zino *et al*., 2008) and this has continued ever since. The body size and nesting characteristics of the shearwater meant that significant benefits to this species were anticipated and serves to show that broad-based biodiversity monitoring is required if we are to understand fully the benefits of rodent removal programmes.

Planning and Public Engagement:

"Plans are nothing, planning is everything" - Dwight D. Eisenhower

Planning is a stepwise process in projects involving rodent control for conservation. Important stages are: project selection, technical and socio-political feasibility assessment, design and operational planning, project implementation and, finally, sustaining the project to secure the biodiversity of the treated area and prevent re-invasion. Details of these processes are comprehensively discussed on the web-sites of the Pacific Islands Initiative (2013) and Cooperative Islands Initiative (2013). These resource kits describe the planning process and, at a basic level, include:

- feasibility study – what can be done, basic considerations, and high level research needs, cost estimates, and significant challenges;
- environmental assessment – the benefits, risks, mitigations and legal compliance required to implement the project, and
- operational plan – a detailed planning document focused on delivering bait into every rodent territory, timed to maximize probability that all rodents will be exposed to the rodenticide, risks to non-target species are minimized and the implementation is legal and can be completed safely by operational staff.

Cromarty *et al*. (2002) provide a good overview of the investment needed in planning and executing a rodent eradication project, focusing on meticulous and robust planning centered upon the principles of eradication and peer review. The planning must be robust enough to ensure that the implementation of a rodent eradication will have a high likelihood of success, is within budget, fully sanctioned by appropriate authorities, can be implemented safely, any changes or unanticipated events situations can be overcome and the entire programme carried through with available resources. Peer review helps to identify aspects of the project that may put the eradication at risk and provides suggestions on how to improve plans. Organizations such as the Island Eradication Advisory Group (IEAG), managed by the New Zealand Department of Conservation, or Island Conservation Eradication Advisory Team (ICEAT), managed by Island Conservation, are available to practitioners to engage for support, input or review of their projects.

Throughout the planning process, implementation and future of the project, it is vital that all stakeholders are engaged. Stakeholders are any party with an interest in the project, and may include landowners, visitors, communities, governments and the general public (Pacific Islands Initiative, 2013). Many of these stakeholders have a vested interest in the outcome of these projects, and because of their associations with the islands, may have important knowledge and insight into local conditions that can be considered in the eradication planning process.

Long-term control

Sometimes vulnerable plant and animal communities require protection from the depredations of alien invasive rodents when eradication is logistically impossible. In such cases, it has proved possible to initiate long-term protection plans that have met with considerable success. Such projects generally involve many of the same features and considerations as eradication but, by their very nature, require prolonged commitment of financial and other resources. Often in these projects it is possible to reduce the amount of effort required by providing protection only at specific times of the year, for example when vulnerable species are nesting. In others, however, long-term protection is provided by the placement of bait boxes which are serviced to ensure the permanent availability of poisoned bait. Such lengthy deployment of rodenticide makes necessary careful risk assessment to ensure no unacceptable risks to non-target species. Long-term projects are at risk to a number of influences. In particular, changes in funding commitment can jeopardise continuity and, when anticoagulants are used, the possible development of resistance must be considered.

A typical project of this kind is the protection of Zino's petrel or Freira (*Pterodroma madeira* Madeiran petrel) on mainland Madeira in which rodenticide bait has been deployed annually since 1986 for the protection of the main nest sites of the birds from predation by roof rats (see below). A similar project was conducted on the Galapagos island of Floreana to protect the closely related dark-rumped petrel (*Pterodroma phaeopygia)* (Cruz and Cruz, 1996). On mainland New Zealand, several projects have been carried out for the protection of vulnerable bird species, such as North Island kokako (*Callaeas cinerea wilsoni*), in which areas around breeding sites have been protected from rodents by the long-term deployment of rodenticides and other control measures (Innes *et al*., 1999).

Environmental Considerations

If logistical difficulties accompany nearly all island rodent management schemes, the potential for adverse environmental impacts is also ever present. These impacts and their assessment are addressed, in general terms, in chapter 15. However, several features of island rodenticide applications make careful consideration of potential environmental impacts of special importance. Programmes of rat management, or eradication, on islands are usually conducted in places of extreme environmental sensitivity, with the effect that any impacts that occur may be particularly visible and harmful. Also, food webs on islands tend to be relative simple, allowing rodenticides to move quickly between environmental compartments.

Those who plan and conduct programmes of rodenticide application on islands must generally consider potential impacts on terrestrial, aquatic and marine systems. A very large quantity of information has recently become available concerning the environmental fate of the anticoagulants as a result of the recent review of these substances carried by the European Commission and this information is open to public scrutiny on the website of the European Chemicals Agency (ECHA) (see Chapter 6). This source of data will permit more accurate assessment of potential environmental impacts and should be considered by anyone conducting environmental risk assessments for island rodent control schemes.

The anticoagulants, as active substances, are generally highly insoluble in aqueous media, therefore the risk to the aquatic and marine environments presented by anticoagulants in solution are considered to be very low to negligible. Baits are usually in particulate form, however, and may be available for feeding by aquatic organisms, both in suspension and when accumulated in sediment. The anticoagulants are generally less toxic to fish and invertebrates than they are to mammals and birds, but there may be risks to fish and other organisms if there is considerable run off of bait particles into aquatic environments from treated areas. However, a recent dramatic accident, in which approximately 18 tonnes of brodifacoum bait was deposited into the sea on the coast of New Zealand, has permitted a practical and large-scale assessment of the fate of brodifacoum in the marine environment (Primus *et al*., 2005). The principal environmental effect observed during intensive monitoring was the appearance of brodifacoum residues in certain filter-feeding molluscs and crustacea. No vertebrate fatalities were documented among sea mammals, birds and fish that were present in the vicinity of the spill. This extreme event suggests that significant marine impacts may be unlikely as a result of the much smaller discharges into this environmental compartment that might follow baiting, even by aerial applications, during practical control programmes.

The main impacts of baiting programmes are likely to be in the terrestrial environment via two well-known exposure routes. Non-target animals may consume baits directly (primary exposure) or they may be exposed to rodenticides when they consume, as either predators or scavengers, rodents that themselves have taken the bait (secondary exposure). Less obviously, terrestrial food webs may become contaminated when insects take cereal-based baits and are themselves taken by insectivorous animals. Such potential impacts are now well-documented (Chapter 16) but even with our extensive knowledge of them, and of suitable mitigation measures, island programmes are not always free from adverse impacts (e.g. Howald *et al*., 1999; Salmon *et al*., 2008). Rodent control on the islands of New Zealand has often been carried out with thorough non-target impact assessments. The subsequent publication of the results of these assessments provides comprehensive records of potential pathways of exposure and environmental contamination (see for example Ogilvie *et al*., 1997; Dowding *et al*., 1999; Eason *et al*., 2002).

Such potential impacts make it essential that detailed environmental risk assessments are conducted during the planning of island rodent management schemes. These assessments should follow the standard stepwise sequence of hazard identification, exposure and effects assessment, risk characterisation, risk-benefit analysis, risk reduction (where necessary) and monitoring (van Leeuwen and Hermens, 2004). A recent project using brodifacoum bait to remove rabbit and House mice from an island in the north-east Atlantic provides an example of this approach (Oliveira *et al*., 2010). A hazard to a population of Bertholot's pipit (*Anthus berthelotii*) was identified and further analysis indicated a risk of severe adverse impact through consumption of bait and insects that had fed on bait. Nevertheless, the potential benefits of the scheme were considered to outweigh this risk. A variety of mitigation measures was employed, including translocation of some individuals to a neighbouring island, taking others into captivity, covering bait points and the unproven method of deploying drinking stations containing antidote. Monitoring during bait applications revealed the predicted impact and the population was reduced by about 50%. However, monitoring after the control programme showed that the pipit population quickly recovered to its pre-baiting level and, as a result of the removal of mice, which probably predated pipit eggs and chicks and competed for insect food, within two years the pipit population grew to almost four times its former density (Oliveira *et al*., 2010).

Thorough risk assessments do not always assure favourable outcomes. An exemplary procedure of risk assessment, consultation and mitigation planning was carried out by the agencies involved prior to the removal of Norway rats from Rat Island in Alaska (US Fish and Wildlife Service, 2007; see below). In spite of this, unanticipated adverse impacts were observed on non-targets, mainly because of information gaps at the planning stage and operational difficulties which prevented the application of all the mitigation measures considered necessary during planning. Once again, the impacted species are expected to recover quickly and to benefit subsequently from the eradication programme. Observed impacts were determined to be within acceptable levels and to be more than offset by potential benefits (Salmon *et al*., 2008). However, this example serves to remind us that very large enterprises of this kind, conducted in extreme environments, are prone to influences that cannot always be predicted and controlled.

Risk-benefit analysis is often more difficult than risk assessments because the judgements made are usually subjective. Clearly, information is important on the conservation status of species thought to be at risk and those which are intended to benefit from rodent control schemes. Very often, by the very nature of these schemes, the species intended to benefit are extremely rare and valuable. Impacts are often predicted and, indeed, subsequently observed, but in almost every case beneficial outcomes are found greatly to outweigh these impacts. But this observation does not in any way negate the need for carefully conducted and documented risk assessment procedures.

All who use rodenticides in conventional applications adopt practical measures to mitigate their adverse impacts. Similar measures are appropriate in island rodent control but often their implementation adds significantly to logistical difficulties. The most easily-managed mitigation measures involve bait placement by hand and the use of protective bait stations (see above). These bait stations offer protection from consumption of bait by non-target animals that are larger than the targets, protect the bait from weather, prevent contamination of soil and water by holding baits in place, and aid recovery of uneaten bait at the end of treatments. Very substantial eradication schemes have recently been carried out successfully utilising this conservative method. For example the removal of Norway rats from Canna Island (1126 ha) in Scotland using almost 4,400 bait stations (Bell *et al*., 2006) and the removal of House mice and rabbits from Great Salvage Island (270 ha) using about 17,000 bait stations (Oliveira *et al*., 2010). However, the use of hand baiting and bait stations does not, of course, prevent secondary hazard (see Howald *et al*., 1999), although by optimising the quantities of bait applied this hazard is minimized.

As the size of islands intended for control programmes has increased so operations using bait drops from helicopters have come to predominate. Mitigation is significantly more problematic in these programmes (see above). Accurate drops, in terms of area covered and the quantity of bait applied, and the careful timing of applications, are essential so that non-target species at risk are either absent from the treated area or, at least, are not breeding so that food requirements are at a low level. Other mitigation measures, used in both hand baiting and helicopter drops, include the removal of non-targets from the treated area and the use of bait types, such as wax blocks, that are either not attractive to or not easily taken by non-target species.

It is usually possible, after non-target hazards have been identified, risks quantified and mitigation measures planned, to design control programmes in which predicted benefits are found clearly to outweigh potential risks. Many hundreds of such programmes have been carried out (Brooke *et al*., 2007) and in few, if any, have adverse impacts been significant and persistent.

Ethical considerations

By removing rodents from islands using rodenticides for the benefit of other vertebrates (and admittedly for the broader ecosystems they inhabit), we make explicit the fact that we value the lives of some animals above those of others. Our efforts to protect endangered species from rodent predation are often driven by a will to reverse adverse impacts caused by the, albeit unknowing, negligence of our predecessors – in other words ‘we can do it, so we should do it’. But there are those who would argue that these sentiments are entirely misguided; that no animal’s life is worth more than that of another and that once damage is done further human interference is unjustified and compounds our errors – their approach is ‘let nature take its course’. These discussions invoke strong feelings on both sides, nowhere better demonstrated than the legal challenges mounted to prevent recent island rat eradication programmes conducted on the western seaboard of North America (Howald *et al*., 2007).

Ethics in rodent control generally involves discussions about animal welfare and the humaneness of control techniques. Interestingly, research in this area has illustrated striking inconsistencies between the rights of pest animals versus those of research animals (see Chapter 18; Mason and Littin, 2003). Protection levels for research animals vary between countries but a common framework lays the foundation for many laws that apply to the use of animals in research. Many counties follow criteria detailed in an authoritative report produced by the Nuffield Council established in 1991 (Meerburg *et al*., 2008). Generally the criteria are based around the concept of the ‘three Rs’ – refinement, reduction and replacement. The Council criteria highlights that it is important to: 1) provide care for research animals with the results obtained with a minimum of suffering; 2) to search for alternatives to using animals; 3) to provide the opportunity for research animals to lead natural lives before experimentation; and finally 4) any animal experiments with suffering should result in alleviation of suffering in equal or a greater number of humans.

Whilst the use of animals in research can be controversial and the public has strong demands regarding how research animals are treated, there appears to be public apathy regarding the ethics of rodent control techniques. Public attitudes to rodents most likely reflect an historical connection to filthy environments, ill health and more recently impacts on conservation. As a result of this the main criteria for developing rodent control techniques has been increased efficacy and this has led to a situation wherein many commonly-used rodent control methods are inhumane and cause animal suffering. In particular, anticoagulants (the most widely used control technique) can cause discomfort and pain which lasts several days (Mason and Littin, 2003). Increasingly, researchers recommend that the same considerations applied to research animals should be extended to rodent pests (Chapter 18; Littin, 2010). For example, once justification for pest control is clearly established (Litten *et al*., 2004) control methods should not lead to intense pain or discomfort, the duration of pain should be short and escaped rodents should still be able to live natural lives (Meerburg *et al.* 2008). Adhering to the three R’s means that both replacement (prevention of rodent presence) and refinement (i.e. choosing control options with the highest welfare outcomes) becomes increasingly important and it might be argued that this is just as important in conservation rodent control as in the more conventional kind. Reviews investigating existing control technology indicate that more humane methods do exist, namely kill trapping (with well-designed traps that are set properly and frequently monitored), electrocution, fumigation/gassing, along with rodent exclusion and elimination of food supplies and harbourage (Mason and Littin, 2003). However, the application of these techniques in island programmes remains problematic. New industry research must be encouraged in which humaneness and animal welfare are priorities alongside effectiveness. Certainly this approach is gaining traction and New World registration requirements will facilitate the delivery of increasingly humane, species-targeted, low persistence rodenticides (Eason *et al*., 2010b).

Aftermath

Quarantine measures, surveillance and re-invasion responses

Whilst there has been great success in removing rodents, they continue to invade rat-free islands (Russell *et al.*, 2008a). The establishment of rodents on islands from which they have been eradicated sets at nought all efforts expended on their original removal and may be catastrophic for recovering bird, reptile, invertebrate and plant communities. Island biosecurity should consist of pre- and post-control actions, which comprise quarantine, surveillance and contingency responses. Quarantine procedures aim to maintain rat populations at low densities around sites of possible departure, both for ship-borne and swimming rodents. This includes storing cargo in rodent-proof containers, using permanent rodent control devices on vessels and establishing rodent-proof quarantine rooms on islands (Russell *et al.* 2007a, c). For swimming rodents, the size and nature of the water gap appear to be the greatest predictor of invasion risk. Work on Ulva Island (259 ha) indicates that Norway rats are detected arriving once a year from Stewart Island (1,746 km) approximately 800 m away (Broome, 2007). Accordingly, managing islands closer than about 2 km to mainland areas will always be difficult due to higher reinvasion risk, although the presence of strong currents may reduce this 'safe distance'.

It is important to establish surveillance procedures where re-invasion is likely. For this there is the need to set out detection devices to discover and identify invaders, irrespective of the method of movement, before they can establish a viable population (Russell *et al.* 2007b, c). Such devices need to detect rodents at low densities and research has demonstrated that systems involving a combination of measures give the best results (Russell and MacKay, 2005). Many of New Zealand's off-shore islands now have permanent rodent invasion surveillance systems installed on them but these are regularly checked because dispersal of invasive rats happens rapidly (Moors *et al*., 1992). Current best practice suggests that checking should be undertaken at least every six months, as invading rats can establish a large population in less than a year after arrival (Russell *et al*., 2008a). To improve our ability to detect invading rodents research has focused on improving the palatability, attractiveness and durability of rodent baits and on passive monitoring devices, such as tracking tunnels and wax chew-tags, both of which record evidence of the presence of rodents (O'Connor and Eason, 2000; Russell and McKay, 2005). Utilisation of these devices, within an integrated surveillance approach, is currently seen as the most effective option. Although 85% of rat incursions on New Zealand offshore islands have been detected using traps and poison bait stations (Russell *et al*., 2008b).

Once rodents have been detected then contingency responses to incursions should cover at least a 1-km radius around the point of incursion (Department of Conservation, 2006). Suspected evidence of rat incursion should be preserved and independently verified by experts. As speed is vital contingency kits should be stored on islands and made immediately available. These contingency kits need to be maintained and should consist of a variety of detection and elimination devices (Russell *et al.* 2008b). Within these kits, hand-spread, short-life, highly palatable bait is the preferred response and traps may also be used. Finally, trained dogs have been successfully used to locate invading rats and should be employed with other methods to detect rat incursions. In conclusion, provided island biosecurity systems are regularly maintained and tested (Russell *et al.* 2007a), and vigilance is continual, it should be possible to keep islands rat-free even where there is a high likelihood of reinvasion.

Restoration

With the ability to eradicate rodents and defend the islands against reinvasion comes a new conservation goal, that of restoration of island ecosystems. Broadly speaking, island restoration seeks to reconstruct interacting groups of native plants and animals, and usually requires the return of native species after the removal of introduced pests. This is a contentious exercise in ecological terms because it is usually impossible to know what existed prior to rodent invasions. Until the 1980s, island management focused on the prevention of further extinctions, often through translocation of threatened taxa. Over the past 20 years there has been increasing emphasis on the social and economic components that attend island management and restoration (Bellingham *et al.*, 2010). Whilst species translocations remain an essential element of restoration for some islands, there is now a growing realism about the dynamic nature of island ecosystems and in particular the role of past human activity in determining their current state. For many New Zealand islands the role of past fire management by Maori is now generally acknowledged as important (Atkinson 2004), as is the crucial nutrient role that seabirds played in island ecosystems (Towns and Atkinson, 2004). Accordingly, restoration goals for islands now vary greatly from "direct" restoration, where eradication of all non-native species is desired, to other situations where an attempt is made to facilitate ongoing natural processes, such as long-distance dispersal (McGlone, 2006). These latter methods are generally referred to 'passive' restoration and recognise that species pools on islands ecosystems are dynamic over time.

Whilst the removal of rodents is likely to have major benefits for biodiversity, gains are often difficult to quantify. For example, there is an often lack of baseline data before eradication took place together with a lack of local history for translocated native species. Additionally, most of the rodent eradications from large islands (i.e. > 100 ha) have been completed since 1990, so biodiversity responses have been assessed over that short time-frame (Howald *et al*., 2007). Irrespective of this, responses on some islands have been spectacular, especially for birds. For example, on Raoul Island just six years without rats and with few cats, five seabird species that had become locally extinct are again breeding on the island (Thompson *et al*., 2005). In a recent review of New Zealand island restorations, these authors conclude that a robust assessment for native biodiversity gains is only possible for 35 islands on which rodent eradication had occurred within the last 20 years. In summary, known beneficiaries of rodent eradications on these islands include two species of amphibian, 15 species of invertebrates, the northern tuatara (*Sphenodon punctatus*), seven species of geckos, 16 species of skinks, 26 species of terrestrial birds and 14 species of seabirds (Bellingham *et al*., 2010). However, the outcomes of translocations of many of the more cryptic species remain unmeasured, and may remain so for many decades.

This lack of understanding of ecological consequences resulting from rodent eradications has raised some concerns. For example, the benefits of eradications can vary dramatically and unpredictably and there may even be adverse, 'surprise' consequences (Courchamp *et al*., 2003). Sometimes the presence of a few individuals of a species that appear of minor importance can mask powerful interspecific interactions. For example, the removal of herbivorous aliens, such as rabbits and goats, can lead to a release of exotic plants (Kessler, 2002). There are other examples with different trophic relationships (e.g. mesopredator release and/or competitor release, see Courchamp *et al*., 1999; Caut *et al*., 2007). Replicated field studies on the New Zealand mainland have also demonstrated that manipulating single species in isolation can lead to unexpected consequences for other species in the ecosystem. For example, there was the competitive release of rats following removal of the herbivorous brushtailed possum (*Trichosurus vulpecula*) and the competitive release of mice following the removal of rats (Ruscoe *et al*., 2011). Given these issues some authors now suggest that the ongoing success of any eradication campaign is not simply the continued absence of the pest species which has been removed but the recovery of the island ecosystem, with an absence of surprise effects (Courchamp *et al*., 2011).

Case Studies

A series of case studies is provided to exemplify practical approaches to the situations described in the preceding sections and to demonstrate the outcomes of schemes to combat rodents for the benefit of biodiversity. The schemes vary in the ways in which rodenticides were deployed, in the target species and the campaign strategies.

Breaksea Island (1988) – an early eradication of Norway rats using bait stations

Norway rats were first confirmed on Breaksea Island (170 ha) and adjacent Hawea Island (9 ha) in an ecological survey conducted in 1975. At that time the potential of this island to provide a predator-free environment provided excellent motivation for developing rodent eradication technology. The eradication of Norway rats from Breaksea Island was a productive refinement of ground-based work control tested elsewhere. Initially rodents were targeted on Hawea Island, where researchers hoped that new techniques would overcome previous problems with bait station design, neophobia, poison avoidance and poison resistance. Using a system of cleared track-ways, seventy-three plastic drainage pipes (each100 mm wide and 400 mm long) were placed on an irregular 40 m grid three weeks before poisoning. Each tunnel was loaded with two Talon Wax Block (20 g) baits (0.005% brodifacoum) that were checked and replenished daily. Eradication was achieved in two weeks and provided confidence for the larger Breaksea Island. The Breaksea campaign was similar to Hawea, but stations (*n*=743) were spaced more widely apart (50 m) along contour lines cut at 60 m from the coast to the summit. Large weather-proof stations containing 50 wax block baits were also positioned on inaccessible cliffs and offshore stacks. Eradication was achieved on Breaksea after 21 days of baiting and provided evidence that eradication on a large island (> 150 ha) could be achieved using bait stations and a single control technique.

Madeira (1986 and ongoing) – long-term management of roof rats using permanent bait boxes

Pterodroma madeira (Freira or Zino's petrel) had been thought extinct for decades when, in 1969, a small breeding colony was rediscovered high in the central mountain massif of mainland Madeira. Subsequently, damaged eggs and dead chicks with signs of rodent gnawing were found and it was realised that breeding at the only known colony of Europe's rarest seabird was threatened by roof rats (Zino and Zino, 1986). The eradication of roof rats from Madeira was then, and still is, impossible. Therefore, in 1986, a project was mounted in which climbers using ropes deployed a cordon of 65 permanent bait boxes around the main colony to protect them from predation (Zino *et al*., 2001). The boxes each contained about 2 kg of Talon Wax Blocks (0.005% brodifacoum) which were suspended from wires within the boxes so that they did not touch the sides. Such a large quantity was required because replenishment visits were extremely infrequent. In spite of a risk of disturbing the birds, bait boxes were also deployed on the main breeding ledge. Bait takes in the years after establishment of the boxes were high, particularly from the boxes on the breeding ledge, but then declined. However, there was no improvement of breeding success for the first three years of baiting but, thereafter, there was a marked increase in fledging success (Zino *et al*., 2001). Baiting has been conducted annually since 1986 and would have needed to continue indefinitely. However, on 13th August 2010, a devastating fire swept across the central mountain massif of Madeira, burning all the known breeding ledges just as the petrel chicks were hatching for what would have been a record breeding season. Subsequent soil erosion removed virtually all the nesting burrows from the main ledge and most of the others. In spite of efforts by the staff of the Parque Natural da Madeira and Portuguese Army to construct artificial burrows, little breeding has occurred on the main breeding ledge since the fire and the recovery of *P. madeira* remains uncertain.

Enderby Island (1993) – eradication of mice (and rabbits) by aerial application

Mice were accidentally introduced to Auckland Island (46,000 ha) during the main period of sealing activity in the early 1820s. They then probably arrived on nearby Enderby Island (700 ha) in about 1850, when there was period of attempted settlement in the Port Ross area (Taylor, 1971). In addition to mice, rabbits (*Oryctolagus cuniculus*) were deliberately introduced to Enderby Island in 1865 to establish a food source for castaway mariners and quickly flourished. In the early 1990s mice had only been eradicated from five New Zealand islands (up to 217 ha) using hand baiting techniques. For the campaign on Enderby, a decision was made to use manufactured cereal-based pellets (Wanganui No. 7) containing 0.002% brodifacoum (Torr, 2002). These are palatable and toxic to both mice and rabbits. Two aerial applications of bait (18 days apart) were made using a 'Squirrel' helicopter, with an under-slung bait spreader. Bait was spread at a rate of 5 $kg.ha^{-1}$, with 10 $kg.ha^{-1}$ used in heavily-rabbit infested country. The spreader provided a 40 m wide swath and these were overlapped by 5 m to ensure complete coverage. Given that cereal bait quickly deteriorates in wet conditions the operation was timed for summer to ensure bait remained palatable and to target rabbits better. Several mice showing obvious signs of poisoning were found within three days and no signs of live mice have been observed since baiting despite several intensive searches. Rabbits were not eradicated by the poison but survivors where soon removed using dogs, traps and shooting with spotlighting. Whilst the focus of this control effort was the eradication of rabbits, it showed that with little extra effort other species, in this case house mice, could be targeted using aerial baiting techniques originally developed for rat eradication.

Anacapa Island (2001) - large eradication of roof rats by aerial bait application

Anacapa Island comprises three islets, totalling 296 ha, and was infested with roof rats (*R. rattus*). The topography of the island made hand-baiting impossible and the approached used, aerial seeding, was the first example of this technique employed in North America. The programme faced and overcame significant legal challenges from various groups which tried to prevent implementation on grounds of animal welfare. The programme was also unusual because it was conducted in the presence on the island of an endemic sub-species of ground-dwelling small mammal, the Anacapa deer mouse (*Peromyscus maniculatus anacapae*), on which severe impacts were predicted. Non-target impact mitigation measures were implemented, including the removal of colonies of deer mice, comprising more than 1000 individuals, to secure laboratory accommodation and the similar removal from the islands of the majority of resident raptorial birds. The eradication was successfully conducted using specially-developed 25 ppm brodifacoum bait. Re-introduction of deer mice was carried out successfully and mouse populations quickly recovered to the densities present prior to the applications. Raptor populations also showed significant recovery after the impacts of secondary poisoning and re-release of captive birds. The conservations benefits of the removal of roof rats were quickly apparent. Hatching success among the island's population of Scripp's murrelet (*Synthliboramphus scrippsi*) showed an increase from 42% to 80% and a second small auk species, Cassin's auklet (*Ptychoramphus aleuticus*), nested on the island for the first time since 1927 (Howald *et al*., 2009). A population of Ashy Storm Petrel (*Oceanodroma homochroa*) is also newly established on the island. Anticipated severe impacts on the small passerine, rufous-crowned sparrow (*Aimophila ruficeps*) were seen and, as no specific mitigation measures were prepared for this species, its numbers remained low when censused in 2009.

Campbell Island (2001) – large-scale eradication of Norway rats by aerial bait application

Campbell Island (11,300 ha) is located 700 km south of New Zealand and is extremely isolated. During the 19th century the island was primarily a base for sealing and Norway rats established at that time (McCelland, 2011). Eradication of Norway rats was in the 2001. At that time the established method for aerial application of bait against Norway rats was one baits drop of 8 $kg.ha^{-1}$ followed by another of 4 $kg.ha^{-1}$,assuming a weather forecast of three fine nights after each drop. For Campbell Island the cost of this was unaffordable and the baiting rate was reduced to a single application of 6 $kg.ha^{-1}$, with an intended 50% overlap of bait swaths guided by GPS. Given concerns regarding the low application rate, a bait acceptance pilot trial using non-toxic Pestoff 20R™ cereal pellets was conducted in 1999 using the biomarker Rhodomine. This indicated high bait uptake and the potential for 100% mortality (McCelland *et al*., 1999). As normal, the operation was timed for winter when natural food sources are minimal, and rodent numbers low. The bait used contained 0.002% brodifacoum. Three Bell Jet Ranger helicopters were used to spread 120 tonnes of bait and total island coverage was quickly achieved in four weeks thanks to unexpected favourable weather. Initial monitoring using dogs, trapping and gnaw sticks was undertaken in 2003 and found no sign of rats (King, 2003). Further outcome monitoring has shown that the eradication of Norway rats was achieved. This project has proved that increasingly larger and more isolated islands can be successfully cleared of rats. Operations were facilitated by a reappraisal of accepted aerial eradication methodology and indicated that, with good planning Norway rats can be eradicated with a single bait application on a very large remote island.

Great Salvage Island (2002) – eradication of mice (and rabbits) using a bait station grid and hand-baiting

Great Salvage Island (270 ha) is situated in the north-east Atlantic and is an important breeding station for globally significant populations of Cory's Shearwater (*Calonectris diomedea*), Bulwer's Petrel (*Bulweria bulweria*), Baroli's (previously Little) Shearwater (*Puffinus assimilis baroli*), White-faced Storm-petrel (*Pelagodroma marina*) and Madeiran Storm-petrel (*Oceanodroma castro*). Presently uninhabited, the island was once home to a small seasonal human population and house mice and rabbits were introduced during the period of habitation. The native vegetation had become severely degraded by rabbit grazing and impacts on the breeding seabirds by mice were suspected. A programme to eradicate both species was initiated in August 2002 by the staff of the Parque Natural da Madeira (Oliveira *et al*., 2010). A 1 ha grid was established using GPS technology and a sub-grid of bait stations was established within this at 12.5 x 12.5 m intervals. A total of approximately 17,000 bait stations were set out and initially baited with 150-200 g of a product designed for rabbit control but which was also well-accepted by mice (Pestoff 20R™, containing 0.002% brodifacoum). Precipitous cliffs were baited by hand by climbers using ropes, and very steep slopes and screes, where bait stations could not be set, were hand-baited by placing bait between and under rocks. Initial bait placement took three weeks and this was immediately followed by a second round in which consumed baits were replaced. Finally, rabbit and mouse activity checks were conducted and areas of continued activity were baited a third time. Mitigation measures to protect the important breeding population of Bertholot's pipit have already been described. Eradication of rabbits was confirmed after only three weeks, but the removal of mice took much longer. Talon Wax Blocks (20 g containing 0.005% brodifacoum), which were more impervious to rain, were deployed at all bait stations until March 2003, when all bait was removed from the island. Monitoring for mouse activity was conducted during the subsequent years and the island was declared free of mice. Oliveira *et al*., (2010) have documented the early stages of recovery of native flora and fauna and Zino *et al*. (2008) showed a significant improvement in the breeding success of Cory's shearwater after the eradication. Similar improvement in breeding of this species has been reported as a result of roof rat control on the Chafarinas islands in the Mediterranean (Igual *et al*., 2005). Benefits to the smaller seabird species have not been studied but are to be expected. The removal of house mice has apparently resulted in an increase in the numbers of an endemic subspecies of lizard *Teira dugesii selvagensis*, probably because the effects of predation on eggs and young by mice have been removed. Lizards have been seen feeding on newly-hatched Cory's shearwater chicks (Zino pers. comm.) and consumption of eggs and predation of chicks of the smaller petrel and shearwater species a concern.

Rat Island (2008) – large-scale eradication of Norway rats by aerial bait application

The programme conducted in 2008 to remove Norway rats from the 2800 ha Rat Island (now Hawadax Island) in the Aleutians involved the application of 46 tonnes of 25 ppm brodifacoum bait from two helicopters. Bait applications around two freshwater lakes were conducted by hand. A thorough process of environmental risk assessment and development of mitigation strategies was carried out prior to these applications by the US Fish and Wildlife Service (US Fish and Wildlife Service, 2007). Risks to several wildlife species were identified and the main mitigation measures involved the timing of the baiting, carefully defined rates of application and the use of a bait formulation that was readily biodegraded. The eradication was successful and in 2009 the island was declared rat-free. However, various logistical failures resulted in impacts to non-target species that were greater than anticipated. Only 22 bald eagles (*Haliaeetus leucocephalus*) were thought to be present on the island but 46 were found dead (Salmon *et al*., 2008). 320 glaucous-winged gulls (*Larus glaucescens*) were also found dead, as were individuals of 25 other bird species. It is likely that a high proportion of the casualties found were due to brodifacoum poisoning although, only 24 (out of 34) gulls necropsied, and three other individuals of other species, were confirmed to have been killed by the rodenticide. It was thought that the eagle casualties may in part be due to these birds feeding on dead and dying gulls. Notwithstanding these substantial impacts, post-eradication monitoring conducted in 2009 has shown that the majority of bird species on the island, including glaucous-winged gulls on which impacts appear to have been numerically the greatest, were present in larger numbers than before the programme (Buckelew *et al*., 2011). It remains to be seen whether bald eagles return in the same numbers as before. This is likely to be affected by the extent to which they depended on Norway rats for food. Further monitoring has been recommended to record anticipated benefits to land birds, burrow-nesting seabirds and changes in the vegetative and intertidal communities (Bucklew *et al*., 2011).

What does the future hold for rodent control in conservation?

One thing the future certainly holds is that larger land masses will be tackled to bring the benefits of rodent control for conservation to more endangered species over greater areas. A project currently in progress on the south Atlantic island of South Georgia is the largest ever attempted. The island is partitioned by glaciers and rat-free areas are at risk as glaciers recede to permit Norway rats to move into previously uninfested, wildlife-rich areas of the island. So there is an element of urgency in this project like few others. After a successful initial pilot project in 2011, a second area of 580 square kilometres was treated in 2013 with 183 tonnes of brodifacoum bait by helicopter drop. A third application is planned for 2015. This would result in the island becoming rat-free for the first time since sealers introduced rats to the island in the eighteenth and nineteenth centuries (Long, 2003). Such massive programmes are only possible because of the steady increase in knowledge and experience built up over several decades.

A difficulty brought by an ability to treat larger and larger areas is that it becomes ever more important to be able to make well-informed decisions about the most appropriate areas to treat. Fortunately, recent research has provided a template by which to estimate the conservation benefit of the removal of alien invasive animals from islands based on cost, difficulty and the conservation value of the species to be conserved (Brooke *et al*., 2007).

A significant impediment to the removal of rodents for conservation has been the potential for some of the rodenticides used, in particular the second-generation anticoagulants, to cause unwanted side-effects. These are well-known, predictable and were apparent in some of the projects described in this chapter as case studies. Although, in virtually every case, cost-benefit analysis shows that environmental benefits outweigh the observed adverse impacts, it is important that improved mitigation measures are developed and implemented. Much remains to be done to improve the techniques used by which animals at risk are temporarily removed to safety while rodenticide applications take place.

The development of better mitigation strategies is important because it is apparent that for many years to come conservationists will remain dependent on the active substances that are currently available in order to achieve their conservation goals in rodent pest control. Recent studies are aimed at an re-examination of rodenticides that have gone out of use and are on novel compounds (Eason *et al*., 2010 a,b) but it seems unlikely that any of these will comprehensively replace the use of anticoagulants in the foreseeable future.

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